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THE FRACTURE OF A PARACHUTE HOOK: A CASE STUDY OF THE ROLE OF M--ETC(U)

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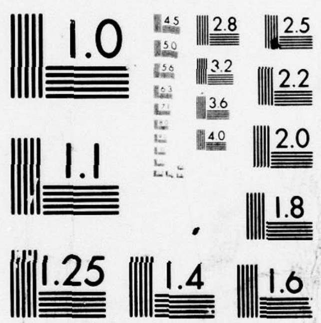

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THE FRACTURE OF A PARACHUTE HOOK: A CASE STUDY OF THE ROLE OF MATERIALS PARAMETERS IN RELIABILITY ANALYSIS

by

L. R. F. ROSE and B. J. WICKS

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SUMMARY

A detailed analysis of the risk of failure for the particular case of a parachute hook is used to illustrate what information is required for that purpose, how much of it is readily available, and in what areas further research is needed. The analysis relies on the use of a full-scale test to identify the mode of failure, and hence the relevant strength parameter. It is concluded that an important role of materials research is to provide an understanding of the factors which can affect mechanical properties, so that the characteristics of the relevant population of structures or components may be more precisely defined, and the variability in strength which can be expected in service may be estimated. A number of topics for further research are discussed, but the practical value of this research will depend on the precision of the results obtained and this cannot be determined beforehand.

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16. *ABSTRACT*

A detailed analysis of the risk of failure for the particular case of a parachute hook is used to illustrate what information is required for that purpose, how much of it is readily available, and in what areas further research is needed. The analysis relies on the use of a full-scale test to identify the mode of failure and hence the relevant strength parameter. It is concluded that an important role of materials research is to provide an understanding of the factors which can affect mechanical properties, so that the characteristics of the relevant population of structures or components may be more precisely defined, and the variability in strength which can be expected in service may be estimated. A number of topics for further research are discussed, but the practical value of this research will depend on the precision of the results obtained and this cannot be determined beforehand.

CONTENTS

1. INTRODUCTION

When a structure, or a structural component, fails by fracture during service, the following questions are usually asked:

(a) what was the cause of fracture?

(b) what is the likelihood of fracture in other similar structures or components also in service?

(c) what corrective actions should be taken to ensure that no further fractures occur, or at least to minimize the probability of such occurrences?

The questions are by no means new, but there is still no systematic and completely reliable procedure for dealing with even some of the more common fractures. There is therefore considerable interest in new approaches or suggestions for improving current methods of failure analysis. In particular Besuner and Tetelman have recently proposed a probabilistic formulation of Fracture Mechanics [1], and an application of Reliability Analysis to a bridge failure [2, 3]—this application is summarized in Appendix I. Our aim in this study is to assess their methodology and to consider its implications for future materials research. To do this we shall use as a case study the service fracture of a hook which formed part of a parachute release assembly. First, we shall adopt the traditional approach to answering the questions asked above, using as far as possible information which is readily available from handbooks or from simple calculations. We then consider what insights or improvements may be obtained from the probabilistic approach, and what additional information is required.

We shall not take into account the possibility of a degradation in strength due to fatigue, creep, corrosion or any combination of these factors. The strength will be supposed to be unaffected by usage. There are cases where such an approach is quite adequate: for example, spacecraft experience high loads at launching and may be considered safe if they will survive this initial load. But our purpose in making this assumption is to simplify the analysis so that it may be more thoroughly understood.

2. A FIRST ANALYSIS OF THE FIELD FRACTURE

The hook has the shape and dimensions shown in Figure 1. It forms part of a release assembly whose purpose is to disengage the parachute once the store has landed. The reported failure occurred in mid-air during deployment of the parachute. The hook fractured across the section AB shown in Figure 1. The larger part of the hook remained attached to the release assembly, the smaller part was lost. A photograph of the fracture surface is shown in Figure 2.

A metallurgical analysis identified the material of the hook as a Cr–Mn–Mo steel, the distribution of trace elements conforming most closely to the specifications for 4145 steel (see Table 1). This type of steel shares the general properties of Ni–Cr–Mo steels (e.g. 4340 steel) and is often used when the higher hardening ability of the latter is not required. The strength of these steels correlates well with their hardness (see [4]). For the present hook, the hardness was determined from ten measurements to be 454 ± 10 on the Vickers scale, using a 10 kg indenter. This corresponds to an ultimate tensile strength (UTS) of 1480 ± 35 MPa (215 ± 5 ksi).

A survey of several case studies of fracture in 4140 steel [5] revealed that a common cause of fracture is the presence of cracks resulting from various postforging operations, for example quench cracks formed in the hardened surface zones produced by flame cutting. These cracks can be avoided by a proper heat treatment but it appears that in the present case the heat treatment was defective. A section, taken normal to the fracture plane *AB*, revealed on etching a pattern of alternating light and dark bands parallel to *AB*. This banding indicates a pronounced segregation of the alloying elements and intermetallic particles within the matrix. A number of small cracks emanating from the surface of the hook could be observed in the dark bands. They

TABLE 1
Metallurgical Analysis (courtesy L. Wilson)

Element	Hook	Specification for 4145 Steel
C	0·44	0·43–0·48
Cr	0·95	0·80–1·10
Mn	0·90	0·75–1·00
Mo	0·18	0·15–0·25
Ni	0·02	—
P	$<$0·02	0·040
S	$<$0·02	0·040
Ti	$<$0·05	—

were most probably formed during quenching. The largest of these had in fact led to the fracture on plane AB. Its extent can be gauged from the zone of darker contrast in Figure 2.

To determine how seriously segregation might have affected the resistance to cracking, the fracture toughness (K_{IC}) of a specimen made up from the hook was measured, and found to be 53 MPa$\sqrt{m}$. Details of the test are given in Appendix II. The value of K_{IC} depends sensitively on the heat treatment, and we do not know the precise heat treatment to which the hook was subjected. The values available from handbooks [6, 7] for 4140 steels of UTS comparable with that of the present hook (215 ± 5 ksi) range between 50–80 MPa$\sqrt{m}$. Thus the measured value is not untypical for this type of steel. Certainly, the fracture occurred not because of a lack of toughness due to segregation, but because of the presence of a relatively large quench crack. With a crack of that size, the hook would have broken under normal operating conditions even if the toughness was 80 MPa$\sqrt{m}$, as the calculations presented in Appendix III show.

Since these hooks were probably cut from a bar or a plate, neighbouring hooks could also suffer from segregation and quench cracking. It was therefore recommended that, in future, hooks should be inspected for cracks before use. If it can be assumed that such an inspection will be carried out, and that hooks which are not rejected are crack-free, there still remains the problem of estimating the probability of failure in such hooks.

3. TRADITIONAL DESIGN CALCULATIONS FOR A CRACK-FREE HOOK

The problem of estimating the probability of failure arises at the design stage, or when a design already in production is being assessed. The traditional procedure is to resolve the problem into the following sequence of questions:

(a) what are the likely loads and the corresponding stresses?
(b) what is the likely site and mode of failure?
(c) what is the relevant strength parameter and what could be a suitable material?
(d) what is the maximum load which can be applied for a given choice of material?

Having answered these questions, the designer then allows for a safety margin: the size of the structure or the load applied to it, or both, are adjusted so that the structure can withstand a load 1·5 times as large as the expected average load. The use of a safety factor of 1·5 is the traditional rule of thumb when it is expected that failure, if it occurs, will be due to static over-loading, and when the structure is believed to be crack-free. It recognizes implicitly that both the load and the strength may deviate from the average values used in the design calculations. The essential idea of Reliability Analysis is to determine explicitly these variations in load and strength, and from that to deduce the probability of failure for any choice of the average values. If this were an easy task it would have become part of the design process long ago. Before we consider the difficulties involved, however, it will be useful to pursue the traditional approach first.

3.1 A Tensile Test

To determine the distribution of stress under load and the likely site and mode of failure, a tensile test was conducted on a crack-free hook mounted in a release assembly. The hook has two loading positions, shown as P and Q in Figure 1, for which the specified weight of store is 600–1,000 kg (1,300–2,200 lbs) and 1,001–2,200 kg (2,201–5,000 lbs), respectively. For our analysis it will be sufficient to consider only loading position P.

During the test the distribution of strain was monitored by seven gauges placed across the plane AB (Figure 1) where the fracture was expected to occur, and where it did in fact occur. The gauges experiencing the greatest strains began to fail when the load reached 50 kN, and readings from all gauges were stopped at that point. Until then the strain had been increasing linearly with load. The variation of strain across AB is shown in Figure 3. It is clear that there is a pronounced concentration of strain near point B associated with a notch in the hook's cross-section at that point. Thus the relevant measure of strength is the notch strength.

The fracture had the macroscopic characteristics of a brittle fracture: it occurred suddenly, without any evidence of extensive plastic deformation or necking being visible on the broken parts. The load at fracture was 104 kN.

3.2 Notch Strength Data

The usual approach when selecting a suitable material for components containing notches is to use the impact energy measured in a Charpy test as an indication of the *relative* notch toughness of the various alternatives. But this test has several limitations which have been discussed in [8]. In particular, it does not supply a measure of the notch strength, which is the property required for calculating the fracture load. The notch strength is usually measured with circumferentially notched circular cylindrical bars, and is defined as the maximum load before fracture divided by the minimum cross-sectional area of the bar. Several factors may affect the notch strength, one of the most important being the size of the specimen used for its measurement. We have the advantage of dealing with a component with similar dimensions to the test specimens most commonly used. But notch strength data is rather scarce, and the most extensive compilation known to us, [9], does not include data for 4140 steels. Thus we must rely on the known similarity in mechanical properties between 4140 and 4340 steels, and use the data for the latter which is shown in Figure 4. This information is evidently not as detailed as one might wish: there is no indication of whether the points shown are the results of single measurements or the average of several, and no indication of the precision of measurement or the intrinsic variability of notch strength. But we shall postpone a discussion of these matters to Section 4. In the traditional approach it is supposed that a single "average" value for the notch strength can be derived from Figure 4.

3.3 The Predicted Fracture Load

To predict the fracture load we need a measure of the stress concentration noted earlier in Figure 3. The maximum stress across the plane AB is 27 ± 1 MPa, when a load of 1 kN is applied at P, according to the strain-gauge measurements.* The maximum stress in a straight rectangular bar of the same cross section and subjected to the same normal force and bending moment as the section AB of the hook is 11·6 MPa/kN, according to the well-known formula for the bending of straight beams. The ratio of these two stresses gives a measure of the stress concentration factor K; $K = (27/11{\cdot}6) = 2{\cdot}3$.

From Figure 4, the notch strength in the transverse direction of a 0·5 in. specimen of UTS equal to 215 ksi, for K equal to 10, 5 and 3 is, respectively, 0·96, 1·07 and 1·19 times the UTS. By extrapolation, we may suppose that a notched specimen with $K = 2{\cdot}3$ would show an effective strengthening of approximately 1·2 relative to an un-notched specimen. We would then predict a fracture load of $\{1{\cdot}2\,(1480/11{\cdot}6)\}$ kN $= 153$ kN.

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* The elastic modulus of alloy steels varies very little from the value of 2×10^5 MPa (29×10^3 ksi), which is generally used in design calculations.

This value can be expected to be an upper bound, for it is based on the notch strength in tension. It would have been more appropriate to use the notch strength in bending, but the relevant experimental data is not available from handbooks. A simple estimate of a lower bound, which is often used in practice, is obtained as follows: the distribution of stress across AB is assumed to be the same as that in a rectangular bar of the same cross-section, and it is assumed that fracture occurs when the stress at B reaches the yield strength σ_Y. With $\sigma_Y = 1{,}170$ MPa ($=$ 170 ksi, see [9]), the predicted fracture load is 101 kN.

This figure is much closer to the measured value of 104 kN, but this may be fortuitous, for the calculation takes no account of the pronounced notch effect visible in Figure 3. For the purpose of comparing traditional calculations with the probabilistic approach it will be sufficient to use only one of the above predictions. We shall use the first one, since that would be the one used if we had no actual measurement of the fracture load.

3.4 The Safe Load

To predict a safe load we must first determine the ratio of the maximum force actually experienced by the hook to the weight of the store which it carries. We shall call this ratio the "amplification factor". The force on a hook during the process of deployment shows two high points, known as the "snatch force" and the "opening shock". The sequence of events during deployment and methods of estimating these peak forces are described in Appendix III. It will suffice here to note that the maximum force is usually the opening shock, and the corresponding amplification factor depends most sensitively on the speed after snatch, which in normal operation is approximately 0·8–0·9 of the launching speed.* The experimental measurement of the opening shock reported in [10] are well approximated by the following equation:

$$\text{Amplification factor} = 0{\cdot}185\,(v - 60),$$

where v is the speed after snatch, measured in knots. Thus for launching speeds of 120 knots and 200 knots, respectively, we may expect amplification factors of 10 and 20.

Consider the case where the launching speed is 120 knots. On the basis of our earlier prediction of 153 kN for the fracture load, and allowing for a safety factor of 1·5, we must require that the store should be no heavier than $\{[153/(1{\cdot}5 \times 10)]\,g\} \times 10^3$ kg, or approximately 1,000 kg (2,200 lbs).† This is precisely the load limit specified by the manufacturer for loading position P.

We have now answered by the traditional approach the questions raised at the beginning of this section, for the particular case of the parachute hook.

4. THE PROBABILISTIC APPROACH

A simple estimate of the probability of failure of a structure or component can be derived from records of its past performance. For example, each use of a release assembly may be considered as a trial of strength with only two possible outcomes: the hook either breaks or it survives. The fraction of trials which ended in a fracture provides the best estimate, in the statistical sense, of the probability of fracture at the next trial. But this estimate is of little value if it is based on the results of only one or a few trials. It is also necessary to derive an upper bound for the probability of failure at a specified confidence level.

The results of past trials of parachute hooks constitute a sample from a "binomial population", that is, one whose members can be classified as either "successes" or "failures". If no failures were recorded in n trials, the formula

$$p^n = 1 - (x/100)$$

gives a lower bound p on the probability of success (survival) at x% confidence level; $(1-p)$ then gives an upper bound on the probability of failure at the same confidence level.

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* The influence of a delayed separation of the canopy from the store is discussed in Appendix III.

† We have taken g, the acceleration due to gravity, to be 10 m s^{-2}.

To the best of our knowledge there have been no failures in crack-free hooks. If we suppose, for the sake of illustration, that there have been 2,000 trials (an average of 2 trials a week for the last 20 years), then the best estimate of the probability of failure at the next trial is zero; the 95% confidence upper bound is $1 \cdot 5 \times 10^{-3}$; the 90% confidence upper bound is $1 \cdot 15 \times 10^{-3}$.

The larger the sample, the closer to the estimate the confidence bounds will be, and hence the more precisely can one estimate the probability of failure. But with structural failures the samples are often small. One cannot usually afford, for instance, to perform more than one full-scale test on a spacecraft. Consider the case where two trials have been performed and no failures occurred. The best that can be asserted with 95% confidence is that the probability of failure in a third trial does not exceed 0·78. This result of statistical analysis clearly does not provide a definite indication as to whether one should proceed with a third trial, or whether one should consider the risk of failure to be intolerably high.

Even when the samples are apparently large, as in the present case, difficulties can arise. Thus it now seems reasonable to distinguish between cracked and crack-free hooks, but one would not have thought of making this distinction before a failure had occurred and the cause of failure been identified. This example shows clearly the inadequacy of simply accumulating a "data bank" of past service records without making a thorough investigation of failures, when these occur. The problem is to define appropriately a "population", such that a future trial may reasonably be expected to be a typical member of that population. This is partly why samples are generally small. In the present case for example, what might have seemed to be a population of hooks should really be divided into two smaller populations of cracked and crack-free hooks. Thus it will not be sufficient, for complex or expensive structures, merely to note that the result of a trial was a success or a failure: the process of failure should be studied more closely. And it is precisely in this aspect of the overall design problem that the traditional skills and knowledge of the materials scientist are most needed.

4.1 Reliability Analysis

Given the frequency distributions of loads and strengths, one can use Reliability Analysis to calculate the probability of failure. Techniques have been developed for estimating the parameters of distributions from limited samples, for dealing with redundant elements and interactions between the components of a structure, and so on. The present case does not require these more elaborate techniques if we assume, for simplicity, that both the loads and the strengths are normally distributed. But this simple case will illustrate why further assumptions often have to be made, so that it becomes difficult to state precisely what confidence can be attached to the final estimate.

A normal distribution is specified by stating its mean, and either its standard deviation or its coefficient of variability (the latter is the standard deviation divided by the mean). Given the coefficients of variability for load and strength one can calculate the safety factor (F) required to ensure a probability of failure (P_f), as described in [12]. The first task therefore is to specify the variability.

The results of 224 measurements of the notch strength of 4340 steel at room temperature, reported in [13], conform closely to a normal distribution, with a coefficient of variability of 0·025. We shall suppose that the same variability would be found in the notch strength of 4140 steel, as indicated by tests on much smaller samples, [14]. There has also been no study as far as we are aware, of the distribution of maximum loads during parachute drops. For the sake of illustration, it will be assumed that the coefficient of variability here is 0·1. A variation of this magnitude can well be expected in view of the rather simple approximations used in estimating the mean load. With these assumptions we find that:

(i) the safety factor $F = 1 \cdot 5$ used in traditional design would ensure $10^{-6} < P_f < 10^{-5}$;
(ii) to ensure $P_f < 10^{-3}$ we need $F = 1 \cdot 33$;
(iii) if the coefficient of variability in notch strength is halved, we would need $F = 1 \cdot 31$ to ensure $P_f < 10^{-3}$.

This last result in particular deserves comment. It suggests that further study of the factors controlling notch strength may be of little value, since a more precise specification of the notch strength hardly affects the safety factor. As this result is due to the relatively large variability in load, it would seem more urgent to sharpen our estimates of the load. But this apparently simple

argument conceals some difficulties. For instance, in section 3·3 we have used the notch strength measured under uniaxial tension, when we should have used the notch strength in bending. This seems to be the common practice, since the notch strength in bending is not given in the handbooks. The variability in bending strength is probably the same as that observed in the tensile case, but the mean strength could be lower than one would expect by considering only the maximum stress at the base of the notch, for the distribution of stress across the minimum cross-section is different in the two cases. In particular, the value of the hydrostatic component of the stress relative to the maximum tensile stress would be substantially different in bending from what it is in uniaxial tension, and so would be the pattern of progressive yielding. If the bending strength is in fact less than we assumed in section 3.3, the maximum permissible weight of store should be reduced accordingly, even though the safety factor remains the same. The problem here is that of providing an adequate characterization of the relevant strength parameter. Even in the present simple case more research seems to be required to determine the notch strength in bending.

5. DISCUSSION

The problem of assessing the risk of failure arises frequently and it must often be answered at short notice. It is therefore important to consider what information is essential for this purpose, how much of it is readily available from handbooks, and in what areas further research is most urgently required. To answer the problem we must determine the load, the distribution of stress under load, the mode of fracture, the relevant strength parameter, and we need to know the variability as well as the average value for both load and strength. In the following discussion we shall consider these aspects in turn, using the results of the present investigation to illustrate the difficulties which can arise in the general case.

5.1 The Load

The greatest uncertainty comes in determining the load and the possible variation in the load. Parachute drops are not perfectly reproducible: there will be variations in the launching speed, in the rate of deployment, there may be gusts or atmospheric turbulence, and so on. In the general case, the sources of variation can be more diverse, as is well illustrated by the case of aircraft structures reviewed in [15]. It will then be more difficult to estimate an appropriate coefficient of variability. The relatively large coefficient of 0·1 which we used in section 4.1 is probably typical of what can be expected in the general case.

5.2 The Distribution of Stress

The distribution of stress in the critical region around B (Fig. 1) could not be determined by the simple calculations often used in engineering practice (the 'strength of materials' approach), because the points of application of load are too close to B; it could perhaps have been obtained by a more elaborate approach, the finite element method for example. But all the methods of calculating stresses involve certain assumptions, and in the case of more complex structures even the more refined techniques do not reveal all the essential features. This was the case in the design of a spacecraft structure [16]: an instrumented test on a prototype ended in fracture even though an adequate safety margin had been allowed for on the basis of a mathematical model in which the stresses were calculated by the finite element method. The model was improved on the basis of information obtained in this first test, the structure redesigned and a second prototype tested. This time the structure did not fail, but the readings obtained from strain-gauges were still quite different from the predictions of the model.

It is therefore sound practice to conduct at least one instrumented full-scale test whenever this is possible. This test should also reveal, as it did in our case, the most likely site and mode of failure.

5.3 The Strength

It is not always evident what should be taken as the strength parameter, and when it is, the relevant documentation may not be readily available. Thus, in the present case we could find

no data on the notch strength in bending. It seems reasonable to assume, as we did, that the strength in bending can be derived from the tensile strength, but this assumption should be submitted to experimental test.

In section 4.1 we also assumed for simplicity that the notch strength is distributed normally, and this in fact described the experimental results quite well [13], but other distributions could give an equally good fit. Coyle *et al.* [17] have found that the normal, log-normal and three-parameter extreme-value distribution could all be used to describe the quite extensive data on the fracture toughness of D6ac steel (a pooling of 404 data points). Statistical tests of goodness of fit could not discriminate between the three, yet they would lead to different estimates of the risk of failure. It is obviously safer to use that distribution which gives the highest risk estimate, but it would be difficult to determine whether this is an optimal choice.

It was suggested in Section 4.1 that it may be more important to determine the average strength rather than the variability in strength. This is the case if that variability is known to be much smaller than the estimated variability in load. But the relevant strength parameter can sometimes exhibit large variations. For example, batches of specimens of D6ac steel, all with approximately the same UTS, were found to have the mean fracture toughness of each batch varying between 40–110 MPa$\sqrt{m}$, [18]. In such cases it would be of considerable practical value to attempt to identify and control the sources of variability.

The range of variability is increased when fatigue, corrosion or creep are involved. Besuner and Tetelman [1] have suggested that future research on fatigue need only concentrate on a better characterization of crack propagation, and that further research on the crack initiation stage may well be of little use. This suggestion is based on a simplified analysis which assumes that the scatter in the time to initiation is considerably larger than the scatter in crack propagation time. If this is so, one obtains much the same estimate for the number of cycles at which the probability of failure is 10^{-3}, whether or not the time spent on crack initiation is taken into account. But the large scatter in crack initiation time reflects our ignorance of the factors which control it, and there is more to be gained in reducing that scatter than in further sharpening our predictions of crack propagation time. Further research may provide us with a better understanding of the controlling factors, or with a means of monitoring the accumulation of damage which culminates in the formation of a crack. We could then reduce the scatter, and thus achieve more efficient design, by being able to define more precisely the characteristics of the population to which the case under study belongs.

5.4 Future Work

In an attempt to define the best directions for future research, it seems logical to consider first the most useful results of previous research. Here we shall be primarily concerned with materials research rather than structural or statistical analysis.

Two well-established results were used in our calculations: first, the similarity in the mechanical properties of hardenable alloy steels, which allowed us to make use of the notch strength data for 4340 steel when the corresponding data for 4145 steel was unavailable; and secondly, the good correlation between hardness and UTS in steels, which provided an estimate of the UTS by a quick non-destructive test. Results of this nature are most valuable to the designer. It should therefore be an objective of further research to attempt to identify such convenient correlations for new materials. This will require extensive testing as well as the formulation of theoretical models with which to understand the essential features which govern the mechanical properties and which can help in suggesting correlations. But good correlations cannot always be found. Thus, in spite of very extensive studies of fatigue we have only found a vague correlation between the endurance level and the UTS [19]; yet even this vague correlation is useful to the designer.

In view of the considerable difficulties in estimating precisely the load and the distribution of stress in a complex structure such as an aeroplane, it seems inevitable that we shall have to rely for some time yet on full-scale tests. An important role of the materials scientist is to help in identifying the relevant strength parameter, to determine the various factors which can influence it so that its variability can be quantified beforehand, and thus to help in setting confidence bounds on the results of full-scale tests.

6. CONCLUSION

The probabilistic approach provides an estimate of the risk of failure associated with a given safety factor, or conversely, an estimate of the safety factor which will ensure that the risk does not exceed a specified value. This additional insight requires additional information, and it can only be as reliable as the information supplied. In our particular case for example, further study would be required to determine the relation between the notch strength in bending and in tension. For the more general case where the strength may deteriorate with usage, it would be valuable to have reliable methods of detecting and monitoring the damage due to fatigue, corrosion and other factors. The development of such methods have of course been part of the traditional concerns of materials research. The difficulty in attempting to define which are the most important areas for future research, or when further research ceases to be cost-effective, is that much depends on the precision of the results which can be obtained. Analyses of the kind presented here do not provide specific answers to these questions, but they can supply useful guidelines for what must in the end be a subjective judgement on the part of those concerned.

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APPENDIX I

Analysis of a Bridge Failure

The problem is to determine the risk of failure in one type of suspension bridge, which we shall call type B, given that a bridge of slightly different type (type A) has failed after 40 years in service. These bridges are suspended by links which consist of two or more eye-bars in parallel. The failure was due to the fracture of one bar in a link composed of two bars; the link failed and then the bridge. The fracture was apparently caused by a combination of corrosion and fatigue.

The problem which Besuner *et al.* [2, 3] consider is to determine the probability of fracture of a type B bar, given that a type A bar fractured after 40 years. The differences between the two types are:

(a) type A bars are made of 1060 steel, type B of 1035 steel;

(b) there are 664 bars in the 3 bridges of type A, and 17,600 bars in the 14 bridges of type B, an average of 220 and 1450 bars per bridge, respectively;

(c) the bars are subjected to fluctuating stresses of amplitude 264 MPa for type A and 141 MPa for type B.

Laboratory tests were performed at 8 different cyclic stress amplitudes (mean stress unspecified) on a total of 50 specimens from type A bars, and the results presented as a log $\Delta\sigma$/log N plot, where $\Delta\sigma$ is the stress amplitude and N the number of cycles to fracture. The straight line giving the best fit, by the method of least squares, was taken to define $\bar{N}$, the mean N. This gave

$$\left.\begin{aligned} \bar{N} &= 10^{13}/(\Delta\sigma)^{4\cdot 34}, \\ \text{standard deviation } (\log_{10} N) &= 0\cdot 216. \end{aligned}\right\} \qquad (1)$$

This is all the information available.

The first step in their analysis is to establish a correspondence between the number of years spent in service and the number of cycles in the laboratory fatigue tests as follows: 1 in 664 bars of type A fractured after 40 years; in the laboratory tests the probability of failure would be (1/664) after 15,000 cycles, at $\Delta\sigma = 264$ MPa. Thus, for type A bars, 40 years are equivalent to 15,000 cycles (one cycle per day, approximately). It is assumed that this equivalence and equation (1) also holds for type B bars. These bars experience a lower fluctuating stress

$$\Delta\sigma = 141 \text{ MPa},$$

so the probability of failure at 15,000 cycles is 10^{-17}. Since a type B bridge has 64 non-redundant links, the probability that it will fail in its first 40 years of service is approximately 6×10^{-16}. Since this is much lower than the average failure rate of $9\cdot 5 \times 10^{-7}$ per bridge year for all U.S. bridges, the authors conclude that the particular type B bridge they were considering is acceptably safe.

Various steps in this analysis are open to criticism but there can be little doubt that the authors' conclusion is correct. We may derive a confidence bound as follows. The 95% confidence upper bound on the probability of failure, if only one failure occurred in 664 specimens, is $4\cdot 455 \times 10^{-3}$, i.e. the sample would be no closer than $2\cdot 615$ standard deviations from the mean and 40 years correspond to at most 18,000 cycles. The scatter at the lower stress level is generally larger than at the higher stress level, a fact ignored by the authors. But if we suppose for illustration that it is $1\cdot 5$ times as large, we find that 18,000 cycles lie at $5\cdot 4$ standard deviations from the mean. Thus a 95% confidence upper bound for the probability of failure of a type B bridge is 9×10^{-13}, which is still much lower than the average quoted above.

The case of the parachute hook offers the following advantages when compared with that of the bridge: (i) the critical component is more easily identified and there is no redundancy—

it is thus easier to define an appropriate "population"; (ii) the loads are better known: there are no sustained loads that may encourage slow crack growth by corrosion; (iii) laboratory tests can be performed on the actual structure rather than on a part of it; (iv) there is no need to establish an equivalence between the number of years spent in service and the number of cycles. These simplifying features allow the scope and limitations of the probabilistic approach to be more clearly recognized.

APPENDIX II

The Fracture Toughness

The specimen and loading configuration used to measure the fracture toughness are shown in Figure 5. This specimen was cut from the hook which failed in service; the crack shown was a pre-existing quench crack. The displacement of the point of application of load increased linearly with increasing load until fracture at a load of 1560 kg. The extent of the pre-existing crack could be observed after fracture. For the calculations which follow it will be taken to be an edge crack of depth 1 mm. The stress across the fracture plane is the sum of a compressive stress P/A, where P is the load, A the cross-sectional area, and the stress in a curved bar due to a bending moment $M = Pd$, where d is the radius of the neutral axis measured from the centre of curvature 0 (Fig. 5). If x denotes the distance measured from the outer surface of the specimen along a radial line through 0, the stress $\sigma(x)$ due to M is given by

$$\sigma(x) = (M/A)\{(b - d - x)/[(b - x)(c - d)]\},$$

where

$$\begin{aligned} a &= \text{inner radius} &&= 6 \text{ mm},\\ b &= \text{outer radius} &&= 13\cdot5 \text{ mm},\\ c &= (a + b)/2 &&= 9\cdot75 \text{ mm},\\ d &= (b - a)/\log(b/a) &&= 9\cdot25 \text{ mm}. \end{aligned}$$

The stress intensity factors due to the compressive stress and the bending moment, which we shall denote by K_1 and K_2 respectively, can be calculated from the expressions given in handbooks, for example [20], p. 2.10 and p. 2.17.

$$K_1 = -(P/A)(1\cdot277\sqrt{\pi l}).$$

With the crack depth $l = 10^{-3}$ m, and P measured in kN, we have

$$K_1 = -0\cdot71\,P \text{ MPa}\sqrt{m}.$$

$$K_2 = 2\,(l/\pi)^{\frac{1}{2}} \int_0^1 F(t)\,\sigma(t)\,\mathrm{d}t,$$

where $t = (x/l)$, and $F(t) \simeq 1\cdot39\,(1 - t^2)^{-\frac{1}{2}}$. Thus

$$K_2 = 4\cdot2\,P \text{ MPa}\sqrt{m},$$

and for the combined stress, we have

$$K = K_1 + K_2 = 3\cdot5\,P \text{ MPa}\sqrt{m}.$$

It follows that the fracture toughness, which is the value of K at the fracture load of $(3\cdot43/0\cdot225)$ kN, is $53\cdot4$ MPa$\sqrt{m}$.

APPENDIX III

Damage Tolerance

In the traditional approach to the design of structures, the structure is assumed to be crack-free, and the objective is to specify a safe-load or a safe-life. A more recent approach, known as fail-safe design, deals with cases where a crack may be present. This approach should only be used if the likely sites of cracking can easily be inspected and if the structure can accommodate a crack large enough to be detected. The structure is then said to be damage tolerant. The designer's main task is to prescribe appropriate inspection intervals such that a crack will have been of detectable size for two or three inspections before it has grown so large as to cause rapid fracture.

The hook under study is not damage tolerant. To show this, consider the stress intensity factor K for an edge-crack at B, along the plane AB of Figure 1.

$$K = 2(\pi l)^{-\frac{1}{2}} \int_0^l F(x)\,\sigma(x)\,dx\,,$$

with

$$F(x) \simeq 1\cdot 12\,(1 - l/w)^{-\frac{3}{2}}\{1 - (x/l)^2\}^{-\frac{1}{2}}\,,$$

w is the length AB, and the stress $\sigma(x)$ along AB, with x measured from B (see Fig. 3), is well approximated by the linear expression

$$\sigma(x) = P\sigma\{1 - (8x/w)\},$$

for $x \leqslant 1$ mm. In this last equation, P is the applied load measured in kN, and σ the maximum stress at B due to a load of 1 kN, which was found from the strain-gauge measurements to be 27 MPa/kN (Section 3.3). From these equations we find on integration that

$$K = 4\cdot 32\,P\,l^{\frac{1}{2}}\,(\pi/8 - l/w)\,(1 - l/w)^{-\frac{3}{2}}\,. \tag{1}$$

This estimate of K leads to the following conclusions:

(i) the reported failure was not caused by a delayed opening of the parachute: the hook would have fractured under normal operating conditions. With the measured values of 53·4 MPa$\sqrt{m}$ for the fracture toughness (Appendix II) and 1·5 mm for the crack depth (Fig. 2), the fracture load, according to equation (1) is only 29·5 kN, which is much lower than the expected average opening shock of 100 kN (Section 3.4). Even if we assumed an upper limit of 80 MPa$\sqrt{m}$ for the toughness (cf. [6, 7]) and a lower limit of 1 mm for the crack depth, the fracture load would be only 51 kN.

(ii) the largest crack which could be tolerated under normal operating conditions, even if the toughness were 70 MPa$\sqrt{m}$, would be only 0·03 mm deep. This is considerably lower than the detection limit of present non-destructive inspection techniques, which is generally taken to be 0·1 mm (cf. [7]). Thus the recommended inspection of hooks before use may be of little avail, for cracks which are small enough to escape detection could be large enough to cause fracture. It would be safer, and probably more expedient, to conduct a proof-test of each hook before use.

APPENDIX IV

The Snatch Force and the Opening Shock

The deployment of a parachute typically occurs in the following sequence, where t denotes the time measured from the moment of release:

(i) $t = 0$ to t_1

The canopy pack and store leave the carrier and move as one body, their horizontal speed decreasing gradually from the launching speed by virtue of air resistance, while their downward vertical speed increases under the action of gravity.

(ii) $t = t_1$ to t_2

The canopy pack detaches itself (or is detached) from the store, and the two move separately with increasingly different speeds by virtue of their different drags. The suspension lines joining the store to the canopy unfold to their natural (unstressed) length and are about to be stretched.

(iii) $t = t_2$ to t_3

The suspension lines stretch, the work done during this stretch being equal to the *relative* kinetic energy of the canopy pack with respect to the store. The maximum total force in the suspension lines in this time interval is called the "snatch force". After snatch the canopy and store move again with the same speed.

(iv) $t = t_3$ to t_4

The canopy pack opens and the canopy unfolds. This leads to a considerable reduction of speed. The maximum total force in the suspension lines during this deceleration is called the "opening shock".

The snatch force and opening shock for a given canopy and store depend most sensitively on the launching speed, and to a lesser extent on the drop distance or the drop time t_1, as illustrated by the following calculations. Three cases will be considered:

case A,

launching speed $u_0 = 60 \text{ m s}^{-1}$ (120 knots),

$t_1 = 1 \text{ s}$;

case B,

$u_0 = 60 \text{ m s}^{-1}$, $t_1 = 5 \text{ s}$;

case C,

$u_0 = 100 \text{ m s}^{-1}$ (195 knots), $t_1 = 1 \text{ s}$.

It will be sufficiently accurate for our purposes to take the density of air, $\rho = 1 \cdot 2 \text{ kg m}^{-3}$, and the acceleration due to gravity, $g = 10 \text{ m s}^{-2}$.

The horizontal speed u and vertical speed v of a freely moving body of mass m are governed by the following equations:

$$\frac{du}{dt} = - R_H u^2 , \qquad (1)$$

$$\frac{dv}{dt} = g - R_V v^2, \tag{2}$$

where R_H and R_V denote the "resistance factors" for horizontal and vertical motion respectively, this factor being defined by the equation

$$R = (\rho D/2\,m),$$

where D, the drag = (cross-sectional area perpendicular to the motion) × (drag coefficient). For the three cases to be considered we shall suppose that the store has

$$\text{mass, } m = 1{,}000 \text{ kg},$$

$$D_H = 1 \text{ m}^2, \quad D_V = 1\cdot5 \text{ m}^2,$$

and the canopy pack has

$$\text{mass} = 20 \text{ kg}, \quad D_H = D_V = 0\cdot5 \text{ m}^2.$$

When the canopy pack is still attached to the store ($t \leqslant t_1$) we shall suppose that their combined drag is $1\cdot5$ m² for both horizontal and vertical motion. Their combined mass is of course 1020 kg.

Further, we shall suppose that the canopy is of the type most commonly used, viz. a flat circular canopy of diameter 20 m; that there are 60 suspension lines capable of supporting a load of 500 kg each at a maximum stretch of 35%. These typical values are all derived from the handbook [11].

The calculations proceed as follows:

(i) A drop time t_1 is specified, and the vertical distance dropped in that time is estimated. (This is simpler than specifying the drop distance and attempting to calculate t_1.) The horizontal and vertical speeds at t_1 are also calculated.

(ii) A time $(t_2 - t_1)$ is specified, and the relative speed and separation at t_2 are calculated. Again this is simpler than specifying the unstretched length of the suspension lines. This unstretched length, which is equal to the separation at time t_2, is usually approximately equal to the diameter of the canopy. So we select, by trial and error, a value of $(t_2 - t_1)$ which gives a separation at time t_2 of approximately 25 m.

(iii) From the relative speeds at t_2 one can calculate the relative kinetic energy of the canopy pack, and by supposing that the lines stretch elastically during t_2 to t_3, one can estimate the maximum force in the lines, since the total work done in stretching is equal to the relative kinetic energy. This maximum force (plus the relatively much smaller drag force on the canopy pack) is the snatch force.

(iv) The snatch speed, i.e. the common speed of the store and canopy pack just after snatch at $t = t_3$, is obtained by using the principle of conservation of momentum.

(v) To calculate the opening shock one must make an assumption regarding the rate of opening of the canopy. The simplest assumption, namely that its drag increases linearly with time, gives results which are in good agreement with experimental observations, see [10]. This leads to the rule of thumb stated in Section 3.4.

We now present the calculations.

(i) *The drop distance and speeds at $t = t_1$*

For all three cases the vertical speed v_1 at time t_1 is obtained by integrating equation (2):

$$t_1 = \int_0^{v_1} (g - Rv)^{-1}\, dv$$

$$= (4\,gR)^{-\frac{1}{2}} \ln \left[\{(g/R)^{\frac{1}{2}} - v_1\}/\{(g/R)^{\frac{1}{2}} + v_1\}\right] \tag{3}$$

where

$$R = (1\cdot2 \times 1\cdot5)/(2 \times 1{,}020) = 8\cdot8 \times 10^{-4}$$

$$(g/R)^{\frac{1}{2}} = 106\cdot6.$$

Let $x = (4\,gR)^{\frac{1}{2}}\,t_1 = 0\cdot 188\,t_1$, then equation (3) gives

$$v_1 = 106\cdot 6\,(e^x - 1)/(e^x + 1).$$

If we calulate v_1 for $t_1 = 1$, 3 and 5 s, and estimate the drop distance d by supposing that the speed inceases linearly between these values of t_1, we have the following results,

t_1 (s)	v_1 (m s^{-1})	d (m)
1	9·97	4·98
3	29·23	44·2
5	46·63	120

The horizontal speed u_1 at time t_1 is obtained by integrating equation (1):

$$Rt_1 = u_1^{-1} - u_0^{-1} \qquad (4)$$

$$u_1 = 100\,[(8\cdot 8\,t_1/100) + (100/u_1)]^{-1}.$$

For cases A and B, $u_0 = 60$ m s^{-1}, $t_1 = 1$ s and 5 s respectively, so that $u_1 = 57$ m s^{-1} and 47·5 m s^{-1} respectively. For case C, $u_0 = 100$ m s^{-1}, $t_1 = 1$ s, so that $u_1 = 92$ m s^{-1}.

(ii) *The speeds and separation at $t = t_2$*

For cases A and C, $u_1 \gg v_1$, so we may safely neglect the vertical speeds in calculating the separation between the canopy pack and the store at time t_2. But for case B, $u_1 \simeq v_1$, so we shall need to consider both the horizontal and the vertical relative motion.

A first integration of equation (1) leads to

$$u = [R(t - t_1) + (1/u_1)]^{-1}, \qquad \text{cf. (4).}$$

and a second integration gives the horizontal distance x moved in time $(t_2 - t_1)$,

$$x = R^{-1} \ln\,[1 + R\,(t_2 - t_1)\,u_1].$$

The horizontal separation h between the canopy pack and the store is the difference of the horizontal distances moved by each, i.e. with the respective resistance factors of 6×10^{-4} and $1\cdot 5 \times 10^{-2}$, we have

$$h = (10^4/6)\ln\,[1 + 6 \times 10^{-4}\,(t_2 - t_1)\,u_1] - (10^2/1\cdot 5)\ln\,[1 + 1\cdot 5 \times 10^{-2}\,(t_2 - t_1)\,u_1]$$

For cases A and C we can construct the following table

$(t_2 - t_1)$ (s)	h (m) for case A	h (m) for case C
0·5	4·5	10·3
0·75		20·1
0·85		24·5
1·0	14·8	31·5
1·25	21·35	
1·4	25·4	
1·5	28·4	

Thus appropriate values of $(t_2 - t_1)$ leading to a separation of approximately 25 m are, for case A 1·4 s and for case C 0·85 s. The relative horizontal speeds are respectively 28·4 m s^{-1} and 45·3 m s^{-1}.

For case B calculations of the vertical separation l proceed along similar lines but the details are more complicated, so we shall only state the results below.

$(t_2 - t_1)$ (s)	h (m)	l (m)	Separation $= (h^2 + l^2)^{\frac{1}{2}}$
1·0	10·9	11·6	16
1·25	15·7	17·0	23·1

With $(t_2 - t_1) = 1 \cdot 25$, we now find that the relative horizontal and vertical speeds are 20·55 m s^{-1} and 23·4 m s^{-1}, respectively.

(iii) *The snatch force*

The maximum force P due to the 'absorption' of the relative kinetic energy may be shown to satisfy the following equation:

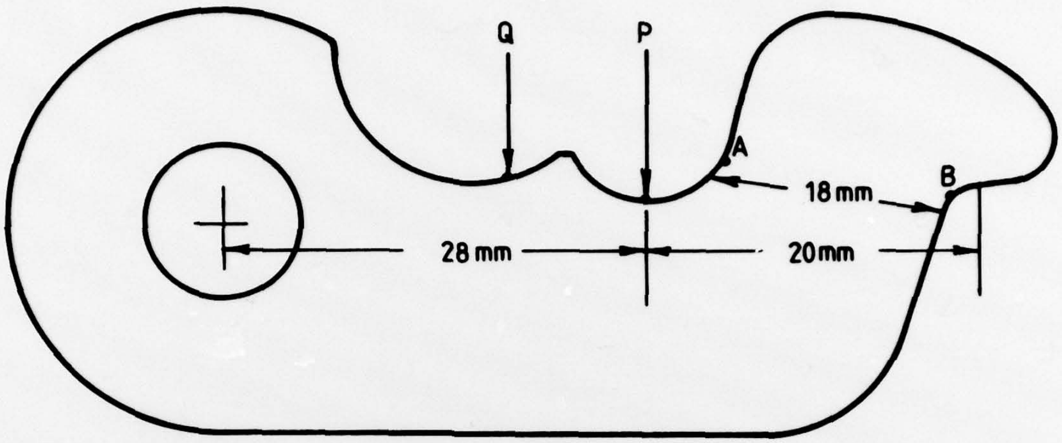
$$P^2 = mv^2 (NS/\epsilon L),$$

where m is the mass of the canopy, NS the maximum total load which the N suspension lines can carry at the maximum extension ϵ. Substituting the numerical values appropriate for the present three cases we have

$$P = 82 \cdot 8\, v,$$

where v is the relative speed of the canopy with respect to the store at time t_2.

For case A we find $P = 23 \cdot 5$ kN. The average drag force during the interval t_2 to t_3 is approximately 200 kN. So the amplification factor associated with the snatch force is 2·37. Similarly, the amplification factors in cases B and C are found to be 2·71 and 4·0 respectively. These values are much lower than the amplification factors during the opening shock which may be calculated, from the formula given in Section 3.4, to be 8·25, 14·5 and 20 for cases A, B and C respectively.



Thickness = 13.5 mm

FIG. 1. HOOK CROSS-SECTION AND DIMENSIONS. P AND Q SHOW THE ALTERNATIVE LOADING POSITIONS; SECTION AB THE FRACTURE PLANE. THE HOOK HAS A UNIFORM THICKNESS OF 13.5 mm.

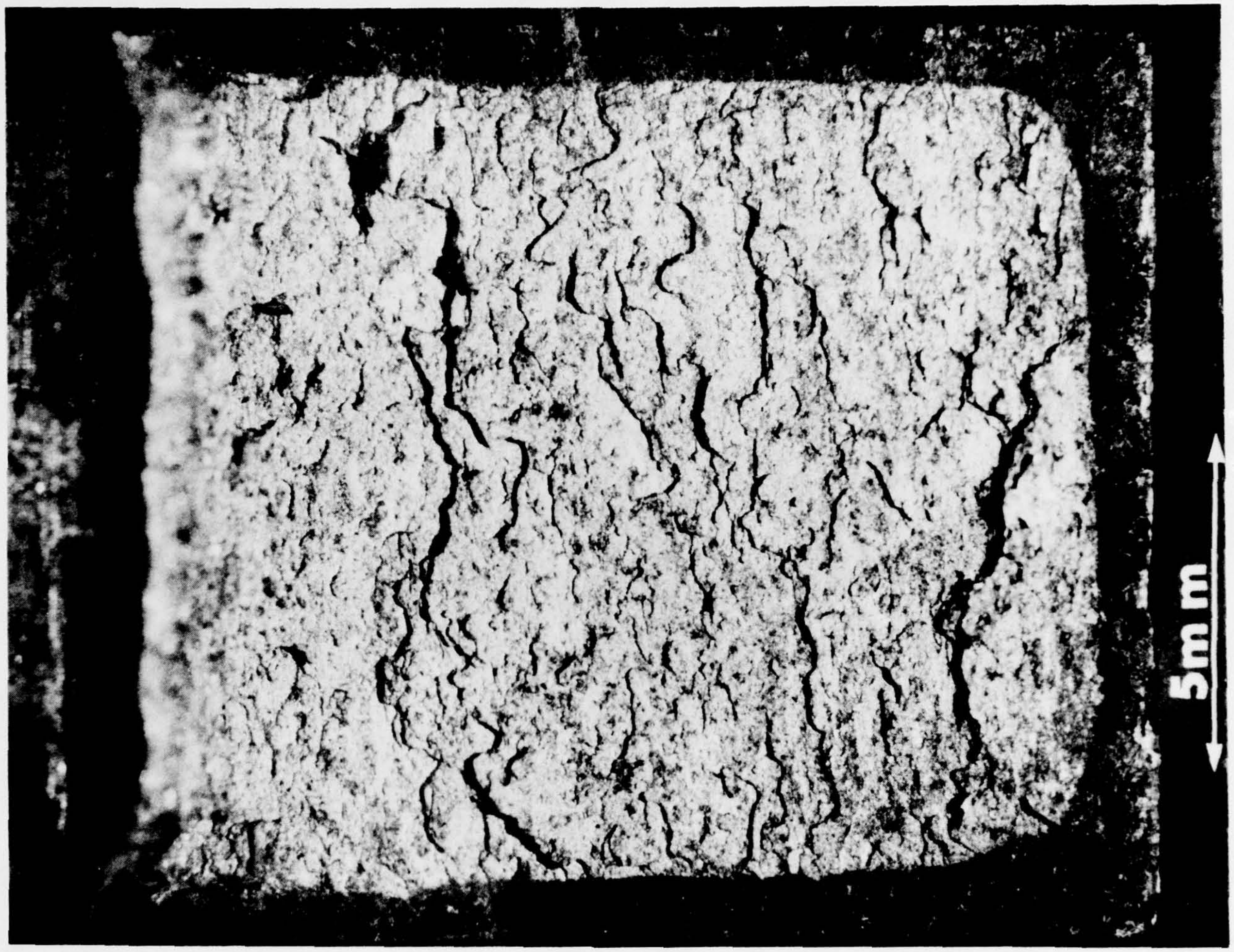


FIG. 2. THE FRACTURE SURFACE OF THE HOOK WHICH FAILED IN SERVICE (MAGNIFICATION X 6).

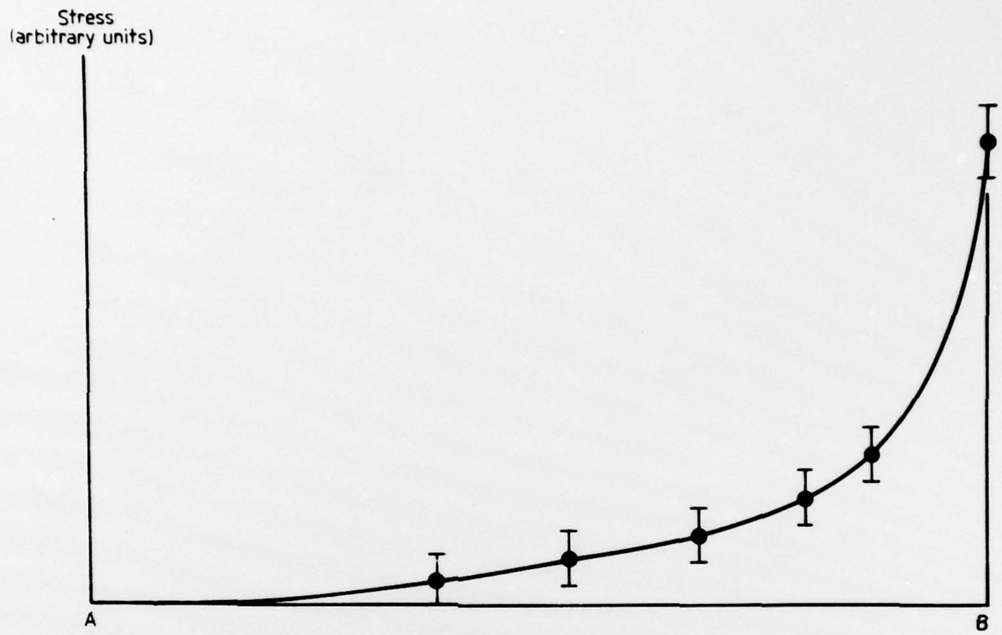


FIG. 3. THE VARIATION IN STRESS ACROSS PLANE AB IN A CRACK-FREE HOOK, AS MEASURED BY STRAIN GAUGES.

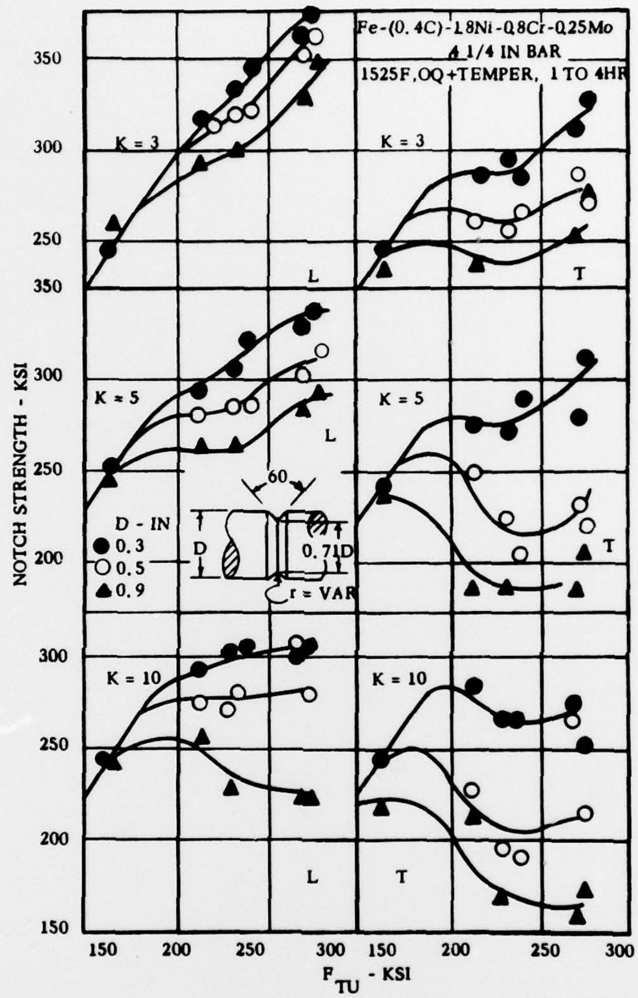


FIG. 4. NOTCH STRENGTH DATA FOR 4340 STEEL FOR VARIOUS STRESS CONCENTRATION FACTORS (K), TENSILE STRENGTHS (F_{TU}) AND ORIENTATIONS (L = LONGITUDINAL, T = TRANSVERSE), FROM [9].

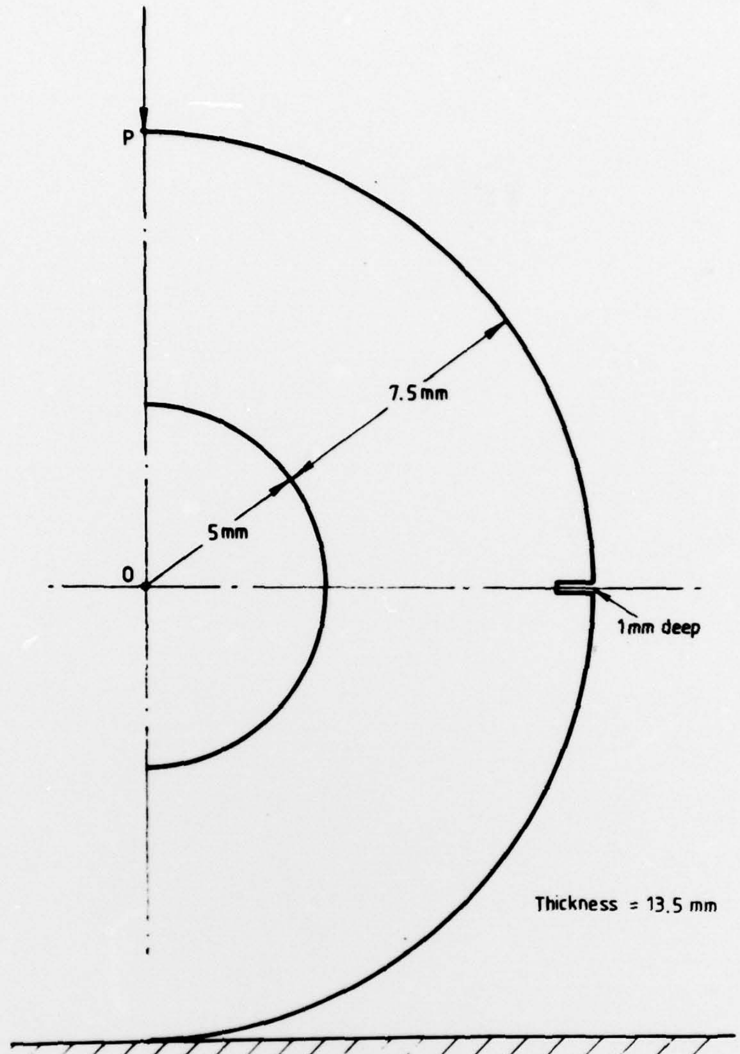


FIG. 5. SPECIMEN USED FOR FRACTURE TOUGHNESS MEASUREMENT.

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